

LUNAR MARE BASALT VOLCANISM: EARLY STAGES OF SECONDARY CRUSTAL FORMATION AND IMPLICATIONS FOR PETROGENETIC EVOLUTION AND MAGMA EMPLACEMENT PROCESSES.

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Introduction: Lunar mare basalt deposits are an example of a vertically accreting secondary crust (derived from partial melting of planetary mantles) superposed on a platform of primary crust (derived from accretional and related heating) [1]. The small total area covered by mare deposits (~17% of the surface) [2] and the small volume ($\sim 1 \times 10^7 \text{ km}^3$) [2] are such that the stratigraphy, fluxes and modes of emplacement can be documented and studied, particularly with the availability of Clementine multispectral imaging [3] and the complementary Apollo and Luna sample collections [e.g., 4-6]. These data can then be used to test models for the origin, ascent and eruption of basaltic magmas, and to document the early stages of secondary crustal formation and evolution. Here we review the emerging new stratigraphy, estimates of flux, the characteristics of surface deposits and implications for modes of emplacement, and emerging constraints on petrogenetic models for generation and emplacement of secondary crustal magmas.

Stratigraphy, Duration and Flux: In general, photogeologic, remote sensing and returned sample studies [7,8] show that mare volcanism began prior to the end of heavy bombardment (period of cryptomare formation [9]), in Early Imbrian and pre-Nectarian times, and continued until the Copernican Period, a total duration approaching 3 billion years. Recent analyses have shown that there were widespread mare regions during the cryptomare period comparable in area to presently exposed maria such as Serenitatis [15-17]. For later deposits, detailed analyses is revealing the range of volumes typical of individual eruptions [13] and Clementine data are revealing the compositional affinities and volumes of units in individual basins and regions [14-16]. The source of heat required for melting and depth of origin is a major outstanding question in the petrogenesis of mare basalts [6, 18] and the onset of mare-type volcanism is a key to the understanding of some types of models [19] for the origin of mare basalt source regions. Increasing detection of cryptomaria has clearly demonstrated that mare volcanism began and was areally extensive [15-17, 20] prior to the formation of Orientale, the last of the large impact basins, at about 3.8 Ga [7]. Presently unresolved is the actual age of onset and areal and volumetric significance of this early mare-type volcanism. New information on the diversity and distribution of mare basalts as a function of time are beginning to accumulate from the analysis of Clementine data. Initial Apollo models emphasized the high-Ti nature of A11 basalts and the low-Ti nature of A12 basalts leading to the hypothesis that melting of the mare basalt source region began at the ilmenite-rich

residuum and deepened with time into the mantle [18]. Remote sensing data from unsampled western maria [21] showed, however, that young high-Ti basalts were widespread and that they were largely of Eratosthenian age [4]. These and subsequent analyses [e.g., 15, 22] have shown that each of the mare basins are characterized by a diversity of mare basalt volcanic fill. Utilizing these data and our own analyses, we have produced a stratigraphic synthesis of mare basalts in individual basins and regions; this synthesis shows that temporal compositional heterogeneity is at least as important as sequential heterogeneity and provides information on the flux. Abundant geologic evidence shows that the vast majority of observed volcanic deposits (>90%, $\sim 9.3 \times 10^6 \text{ km}^3$) were emplaced in the Late Imbrian Period, spanning 600 Ma from about 3.8 to 3.2 Ga [7, 9, 23]; new crater-count data continue to confirm this and to place diverse stratigraphically dated mare deposits in this period [e.g., 17]. A wide range of basaltic compositions was being emplaced in virtually all the nearside mare basins, with earliest and intermediate deposits dominated by (but not confined to; e.g., see [15]) high-Ti basalts; later deposits of this period are dominantly low-Ti and represent the major late fill of nearside basins (e.g., Crisium, Serenitatis, Imbrium, Procellarum). The emerging picture is that the maximum period of production, ascent, and emplacement of mare basalts was between 3.8 and 3.2 Ga; magmas produced during this period were diverse in space and time, but dominated by an early phase of high-Ti basalts. Following this, <5% of the total volume of mare basalts was emplaced during the Eratosthenian Period (spanning ~ 2.1 Ga); a few of the latest flows may extend into the Copernican Period. Predominantly high-Ti basalts were emplaced largely on the central and western nearside (Imbrium and Procellarum). The low overall volume and low average effusion rate of the latest deposits is partly due to global cooling and the increasingly compressional state of stress in the lithosphere [18], both factors minimizing production of basaltic magmas and their ascent to the surface. A key conclusion is that the heat source for melting of parental material was operating for possibly as long as an additional 2 Ga, and that it was producing high-Ti basalts extruded over a limited portion of the lunar surface. In summary, mare deposits are testimony to the production and extrusion of mare basalts for a period of at least 2 Ga and perhaps as long as 3 Ga; surface volcanism, however, has not been volumetrically significant on the Moon since about the late Archean on Earth. Mare volcanic flux was not constant, but peaked during the Late Imbrian Period; average global volcanic output rate during this peak period was $\sim 10^{-2} \text{ km}^3/\text{a}$,

comparable to the present local output rates for individual volcanoes on Earth such as Kilauea, Hawai'i. Some single eruptions associated with sinuous rilles may have lasted about a year and emplaced 10^3 km^3 of lava. The flux was variable in space and time during this period, and the patterns revealed by the stratigraphy show evidence for regional concentrations of sources and compositional affinities; these patterns are the basic data for defining the configuration, size, and density of mantle source regions throughout the period of mare basalt emplacement. Evidence for emplacement style suggesting that magmas are commonly delivered to the surface in large quantity through dikes originating from depth include areally extensive lava flows [25], sinuous rilles attributable to thermal erosion [26], lack of large shield volcanoes [27], and evidence for the emplacement of large dikes in the vicinity of the surface [28]. The low density of the lunar highlands crust provides a density barrier to the buoyant ascent of mantle melts [29] and ascending diapirs are likely to stall at a neutral buoyancy zone there, before reservoir overpressurization propagates dikes toward the surface [9]. In summary, these data provide an emerging picture of the nature, flux, and mode of emplacement of lunar mare deposits.

Testing Models of Petrogenesis and Modes of Emplacement: These data on mare heterogeneity in time and space can be used to test models for the petrogenesis and mode of emplacement of mare basalts. As an example, in one model [19], the dense ilmenite-rich (with high concentrations of incompatible radioactive elements) and underlying Fe-rich cumulates forming at the base of a stratified lunar differentiate are negatively buoyant and sink to the center of the Moon. Subsequent radioactive heating causes mantle melting and diapiric rise of magmas. The low-density highland crust acts as a density barrier to the buoyant ascent of mare basalt magmas, likely causing them to stall and overpressurize, sending magma-filled dikes to the lunar surface. This density-barrier factor may be responsible for much of the

areal difference in distribution of mare basalt deposits, most notably in the nearside-farside asymmetry [9]. We compare the predictions of this model to the stratigraphic record of mare basalt magmas and find qualitative agreement with this petrogenetic model. The emerging details of the stratigraphic record, and increasing ability to read throughout the primary crustal density filter permits us to begin to constrain aspects of this model and examine others.

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